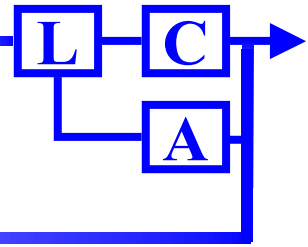# Synchronous Maneuvering of Uninhabited Air Vehicles
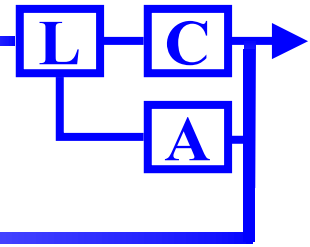

Olivier Laplace

Princeton University

FAA/NASA Joint University Program

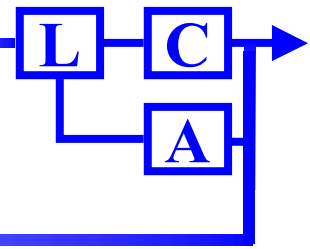**Quarterly Review - June, 2001**

Outline

- **Introduction**

- **Problem description**
  - Aerobatics program specification
  - Formation flying
  - Trajectory parametrization

- **Coordination methods used**
  - Maneuver assignment
  - Regrouping on a circle
  - Simulation results

- **Concluding remarks**

Aerobatics program

L **C** **A**

- **Objective:**
  - Demonstrate coordination of a group of UAV,
  - Through the execution of an aerobatics program.

- **Aspects of interest:**
  - Maneuver assignment:
    Maneuver distribution over aircraft is not specified.
  - Maneuver synchronization:
    Maneuvers must be flown by waves.

Aerobatics program

- Organized as a layered oriented graph of maneuvers
- Easily specified through a file
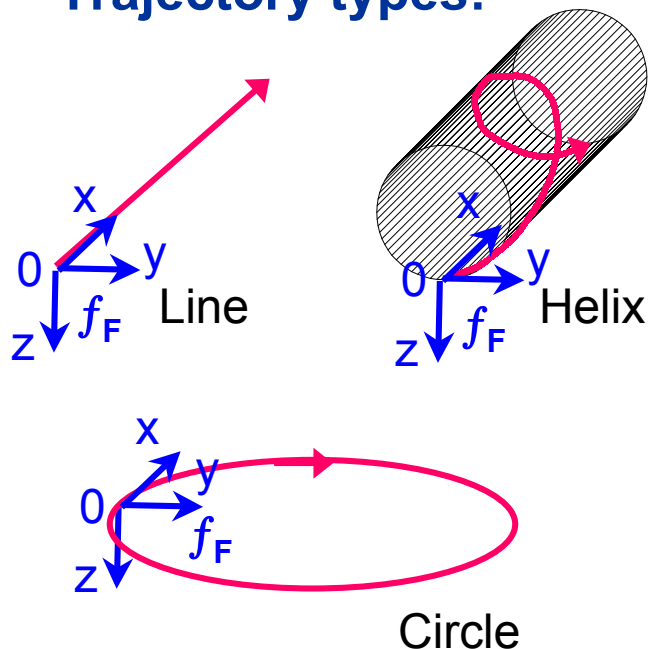
Entry ... End
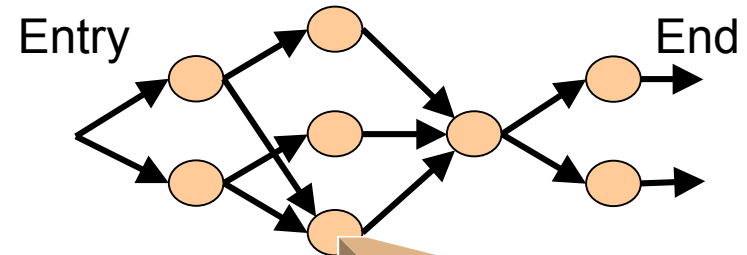
Maneuver j

Characteristics
Number of slots
Next maneuvers
Incentive

Trajectory characteristics
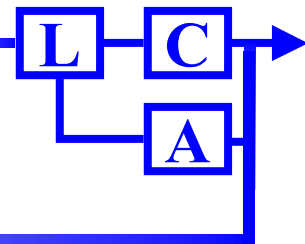
Maneuvers are made of basic trajectories, whose equations are known to aircraft. They can be adapted as follows.

- **Trajectory types:**

  x
  0 y
  z f_F Line

  x
  0 y
  z f_F Helix

  x
  0 y
  z f_F
  Circle

- **Trajectory positioning and orientation:**

  Maneuver frame
  x
  0 y
  z
  f_F

  Rotation angles
  Θ
  Ψ
  x
  Φ

  Origin
  0 y
  z f_E Earth frame

- **Trajectory parameters:**
  - Speed
  - Radius
  - Roll rate
  - Duration
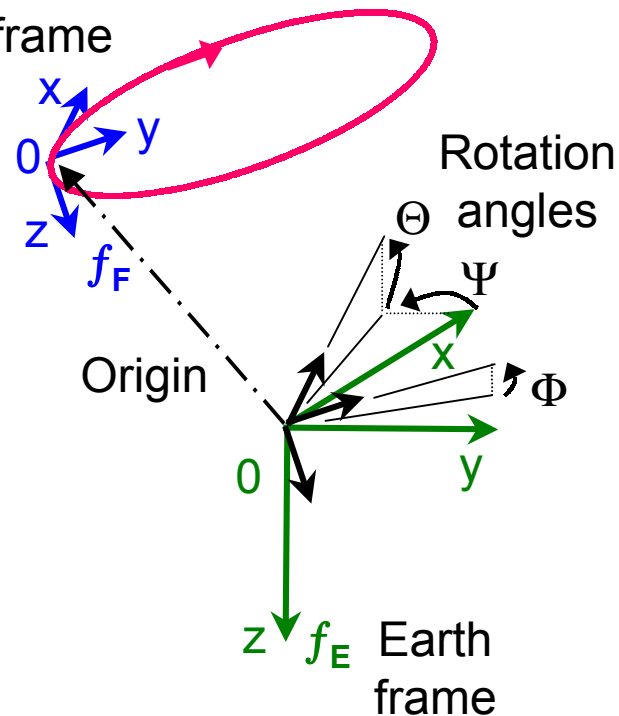
Formation flying
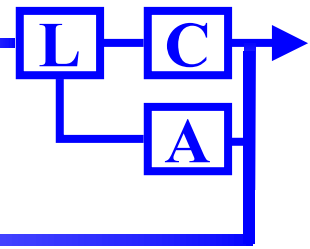
- **Roles in the diamond formation:**

Leader

Formation center

Virtual leader

D

D

D

D

Follower 1

Follower 2

Follower 3

D = aircraft spacing

- **Offset trajectories:**

x y 0 z f_F Line

x y 0 z f_F Helix
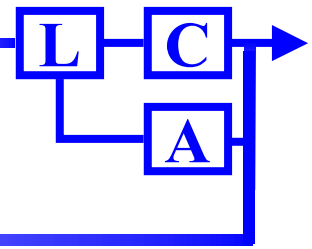
x y 0 z f_F Circle

– reference trajectory
– aircraft trajectory
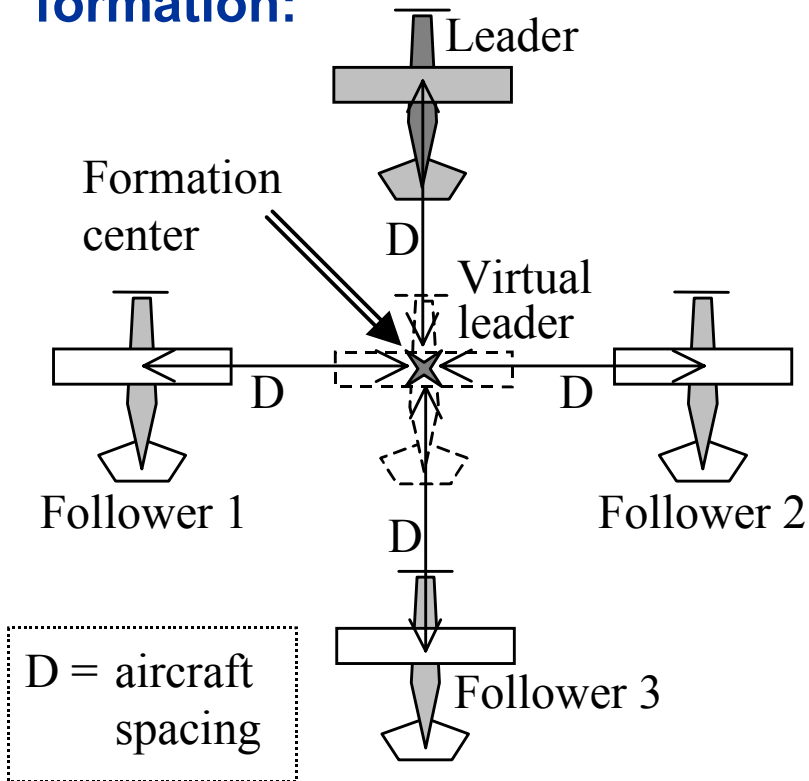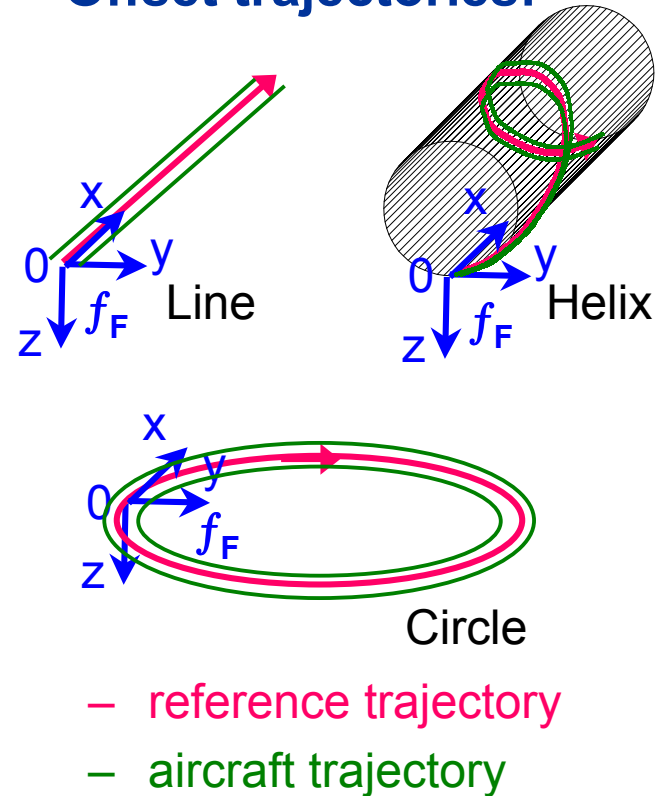
Trajectory parameters (speed, radius, and roll rate) are also adjusted so that aircraft stay in formation, if they track their offset trajectories as computed.

Aircraft position on trajectory

- **A trajectory parametrization, the Equivalent Path Length (EPL):**
  - EPL $\rightarrow$ aircraft position map, invertible for simple trajectories.
  - Aircraft speed specified through EPL derivative:
    $\dot{s} = 1$ corresponds to trajectory normal speed.
  - Aircraft with same EPL on their own offset trajectories are in formation.

- **In our case:**
  - Trajectory are parameterized by time.
  - We take EPL = time on trajectory.

- **EPL use:**
  - Predict aircraft future position knowing the aircraft EPL and its derivative.
  - Compute the time necessary for an aircraft to reach a particular position on its trajectory (e.g. the end).

Aircraft
EPL, s

$\dot{s} > 0$
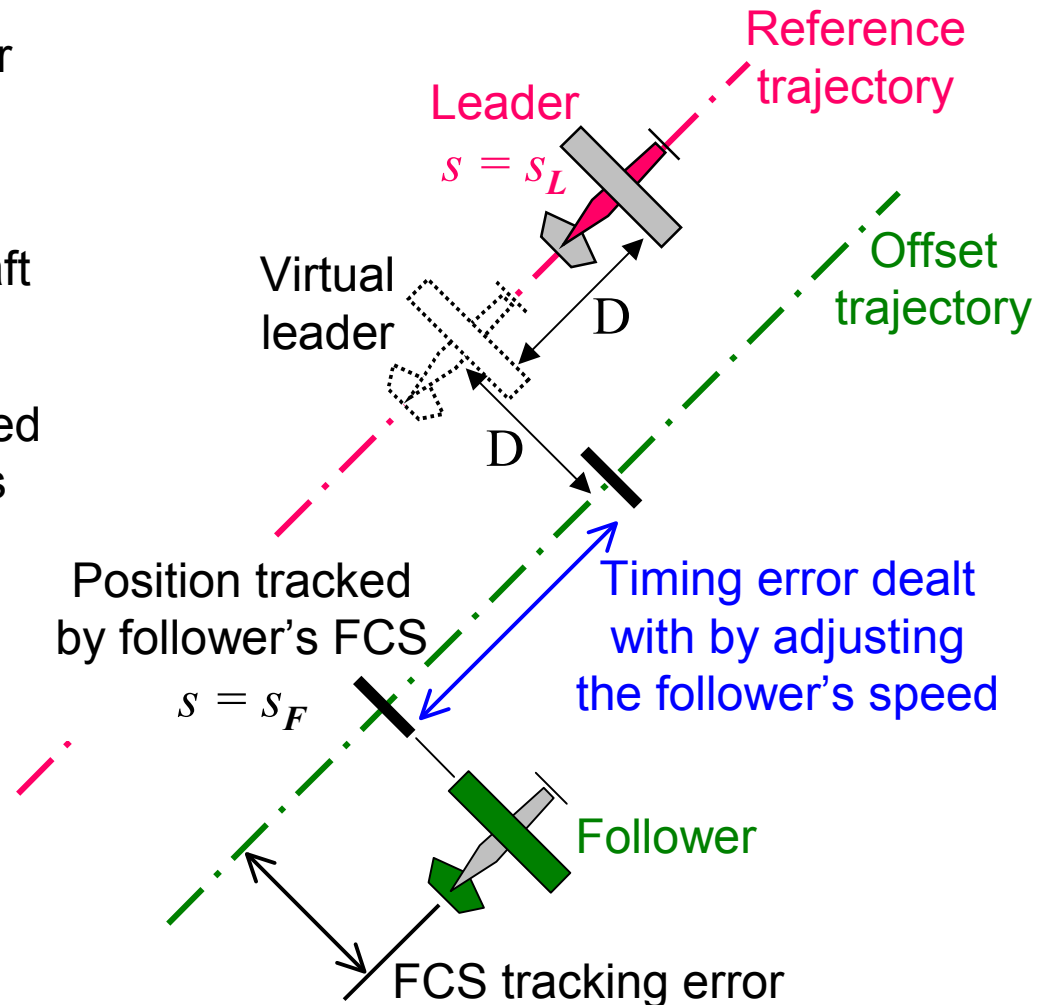
$s = 0$

x

y $f_\mathbf{F}$
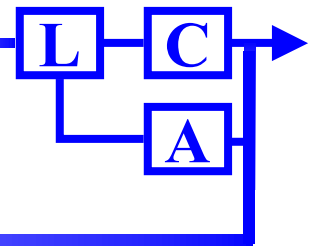
z
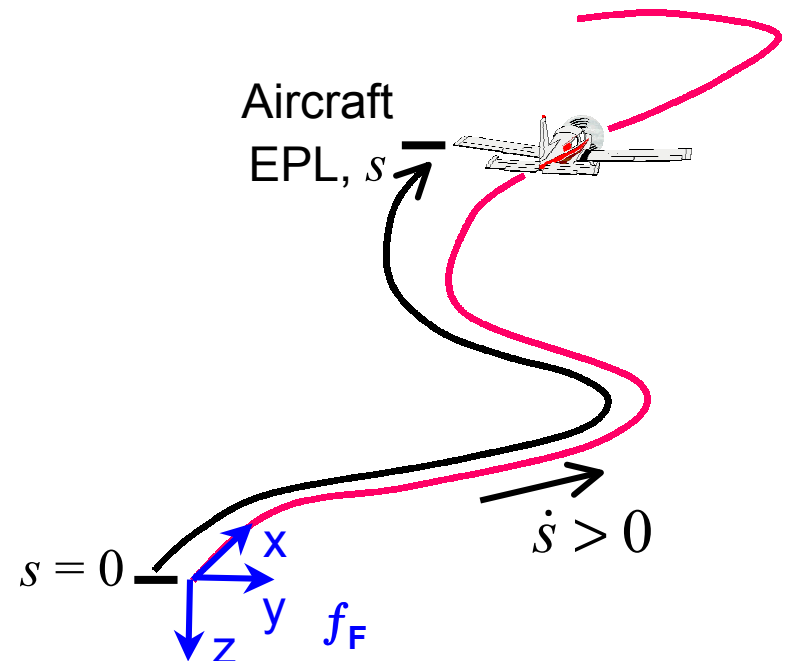
Staying in formation
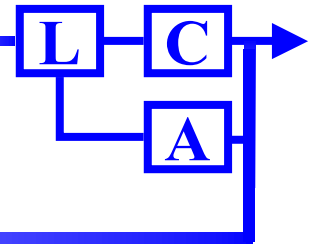
- Leader sets the virtual leader EPL equal to its own.

- The FCS tracks the nearest point on the trajectory (aircraft behave as beads on a wire).

- The follower speed is adjusted to keep up with the leader as follows:

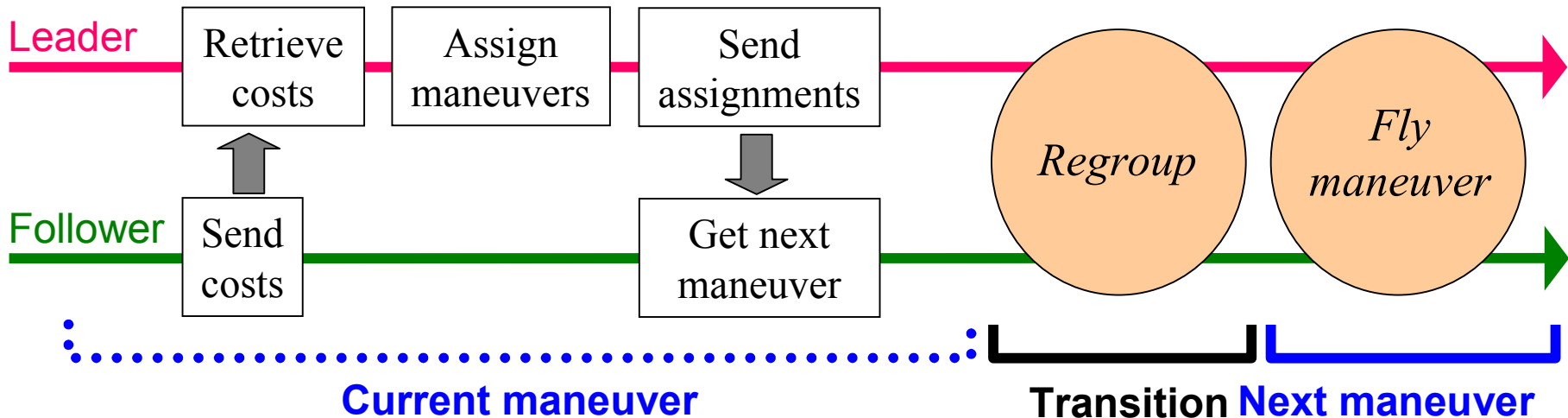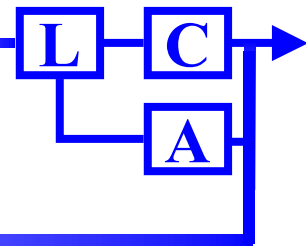$$\dot{s}_F = \dot{s}_L + K\left(s_L - s_F\right)$$

Reference trajectory

Leader

$s = s_L$

Virtual leader

D

Offset trajectory

D

Position tracked by follower's FCS

$s = s_F$

Timing error dealt with by adjusting the follower's speed

Follower

FCS tracking error

Maneuver assignment

- Trajectory assigned to maximize team reward for flying the program:

$$\sum_{\substack{\text{maneuvers}\\\text{flown}}}\left\{(\text{maneuver's incentive}) - \sum_{\substack{\text{aircraft}\\\text{flying it}}}(\text{cost to fly the maneuver})\right\}$$

- Centralized scheme used.

- Done before each wave of maneuvers.

Leader: Retrieve costs → Assign maneuvers → Send assignments

Follower: Send costs → Get next maneuver

Regroup   Fly maneuver

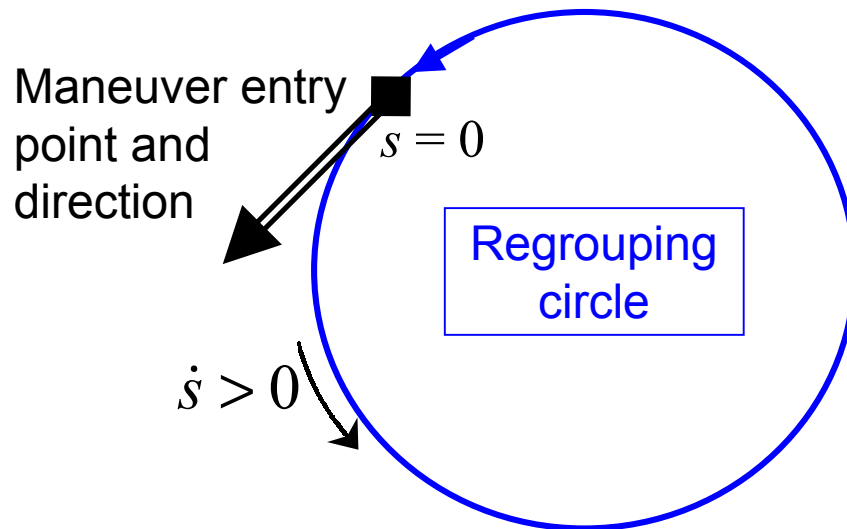Current maneuver   Transition   Next maneuver
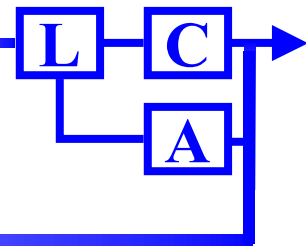
Regrouping

- **Regrouping trajectory:**
    - Horizontal circle of default radius.
    - Tangent to the maneuver at its beginning.
    - Flown at default speed.
    - Same for all aircraft.
    - Origin of EPL on the circle at the maneuver starting point.
    - EPL length of the circle = S .

Maneuver entry point and direction

$s = 0$
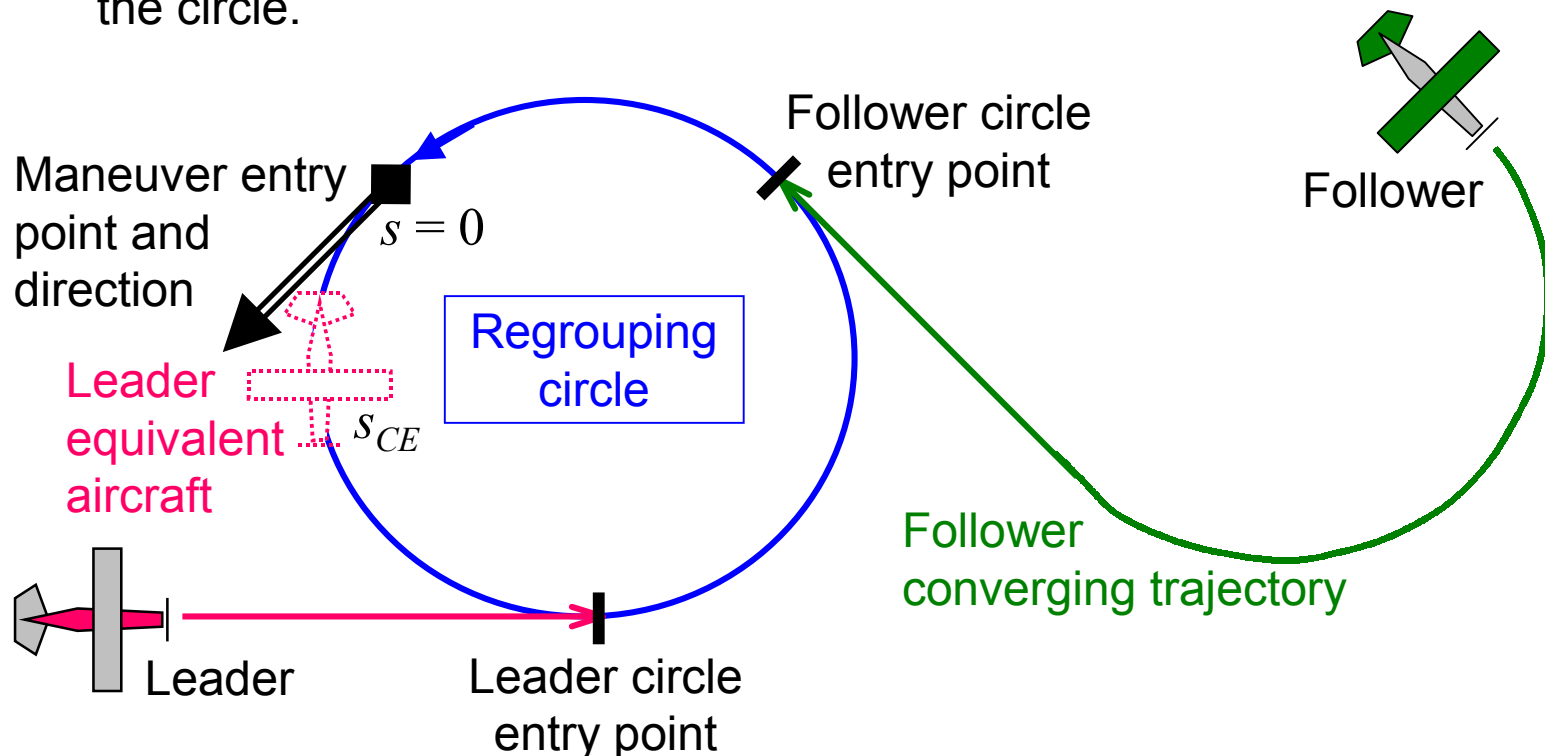
Regrouping circle

$\dot{s} > 0$

Regrouping

- **All aircraft:**
  - Compute a converging trajectory that brings them tangentially on the circle.
  - Compute their entry point on the circle.
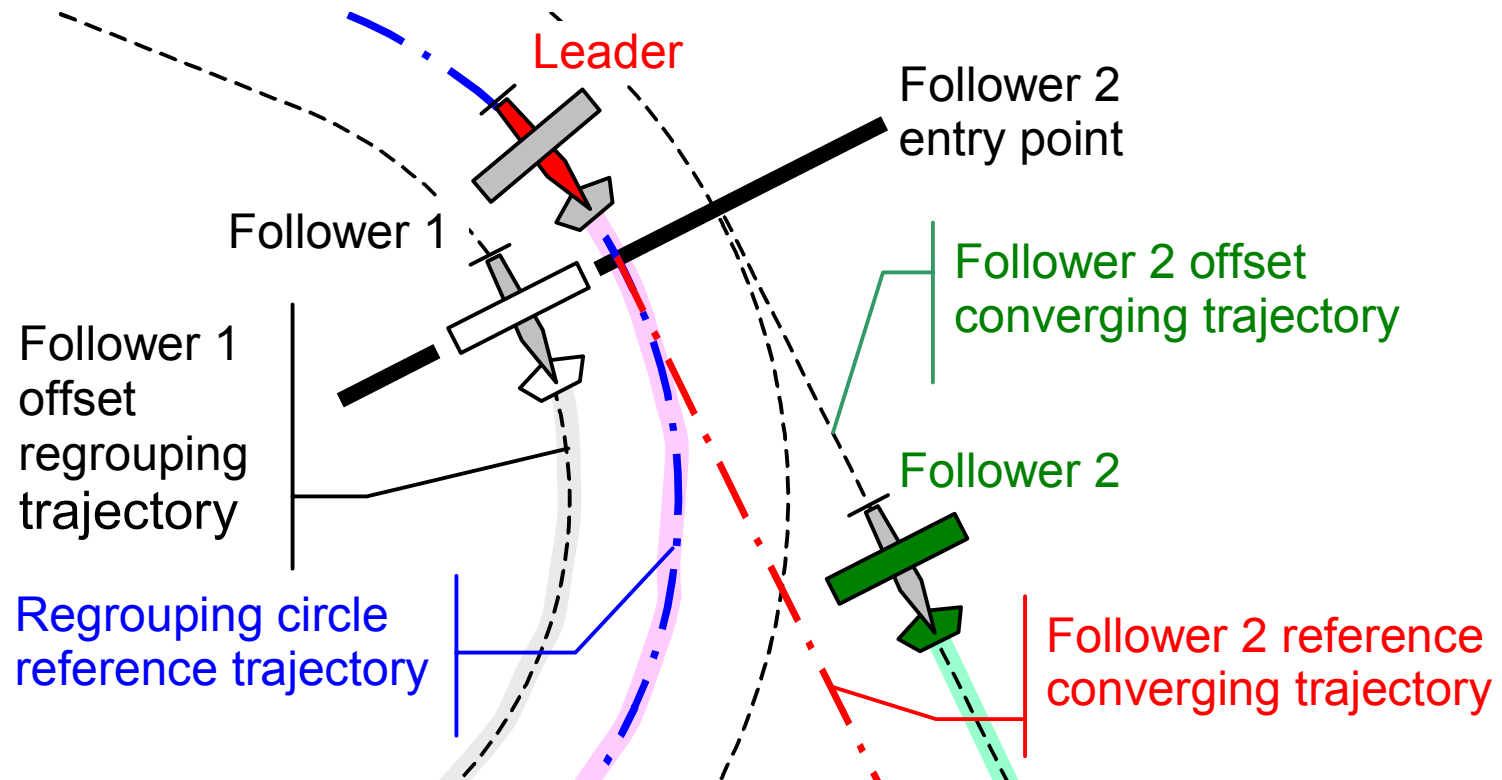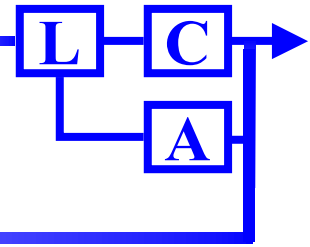
- **Leader:**
  - Flies at normal speed.
  - Periodically broadcast its circle equivalent EPL, s_{CE}, and speed, $\dot{s}$.

Maneuver entry point and direction

$s = 0$

Follower circle entry point

Follower

Leader equivalent aircraft

s_{CE}

Regrouping circle

Follower converging trajectory

Leader

Leader circle entry point

Regrouping

- **Follower:**
  - Adjust its speed to meet the leader when entering the circle.

$$\dot{s}_F = \dot{s}_{slow} + \left[\left(\dot{s}_F + \frac{\Delta s_{CE}}{T} - \dot{s}_{slow} \right) \mathrm{mod}\, \frac{S}{T} \right]$$

$$\text{if} \quad \dot{s}_F > \dot{s}_{fast} \quad \text{then} \quad \dot{s}_F = \dot{s}_{fast}$$

T = time for the follower to get to the circle

Leader position when follower enters circle

Follower circle entry point

Follower

Maneuver entry point and direction

$s = 0$

Δs_{CE}

Regrouping circle

$\dot{s} > 0$

Follower converging trajectory
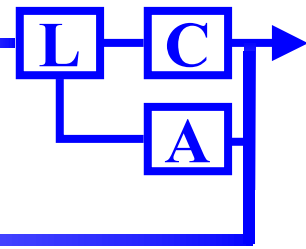
Leader

Leader circle entry point

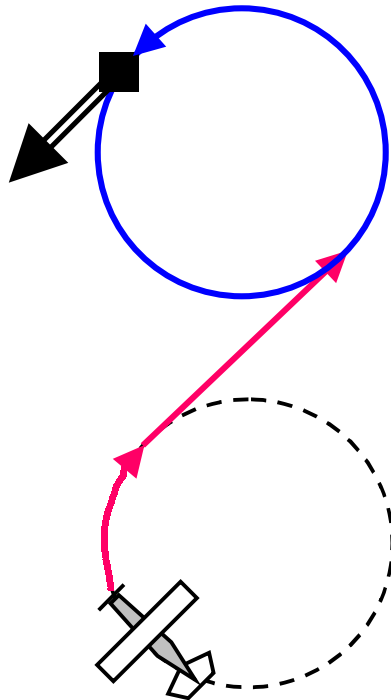# Use of offset trajectories for follower circle entry

Transition trajectory generation

- **Idea in 2 dimensions:**
  - Go to any point arriving with the desired orientation using two circles and a line.
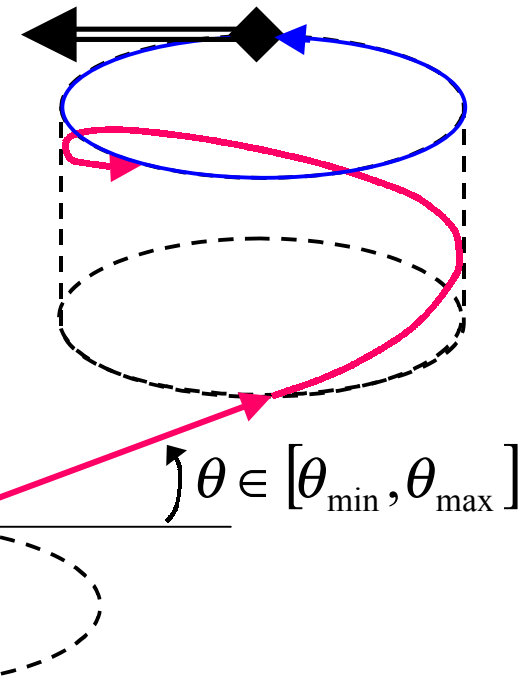
- **Extension to 3 dimensions:**
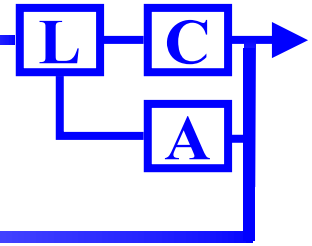 - Use the line to climb, and if needed add an helix.

The slope, θ, must stay in the range where the aircraft can maintain any speed in

$$\left[\dot{s}_{slow}, \dot{s}_{fast}\right]$$

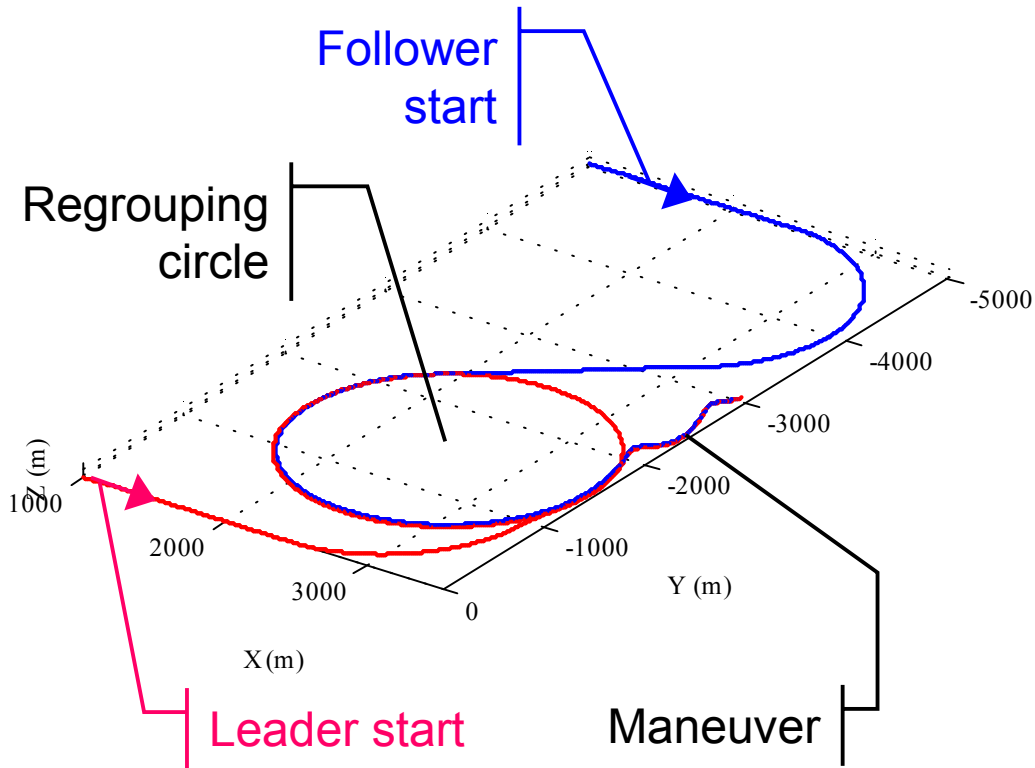$$\theta \in \left[\theta_{min}, \theta_{max}\right]$$

- **Alternative method:** Motion planing for an hybrid automaton (E. Frazzoli and E. Feron).

Simulation results

- **3D trajectory:**

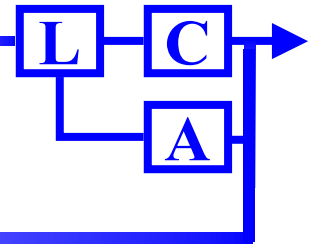- **Aircraft positions in the horizontal plane versus time:**

Follower start

Regrouping circle

Leader start

Maneuver

Z (m)

1000

2000

3000

X(m)

0

-1000

-2000

-3000

-4000

-5000

Y (m)
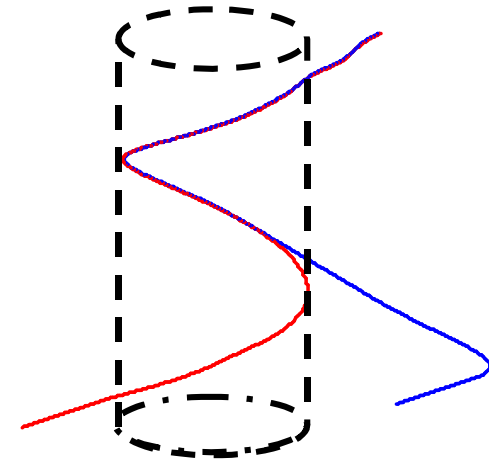
Concluding Remarks

- **Aircraft synchronization:**

  - Regrouping of aircraft on a circle has been demonstrated.

  - Aircraft exchange signals when they are ready to start the maneuver.

  - Aircraft can be on different circles, thus one can synchronize the execution of several maneuvers.

- **Future work: Collision avoidance**

  - Necessary because of limited precision of the trajectory tracking control law.

  - Can be performed using a 1/r repulsive potential since aircraft relative speeds are small once they are in formation.